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NONLINEAR CONTROL OF A REUSABLE ROCKET ENGINE FOR LIFE EXTENSION

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Abstract

This paper presents the conceptual development of a life-extending control system where the objective is to achieve high performance and structural durability of the plant. A life-extending controller is designed for a reusable rocket engine via damage mitigation in both the fuel (H_2) and oxidizer (O_2) turbines while achieving high performance for transient responses of the combustion chamber pressure and the O_2/H_2 mixture ratio. The design procedure makes use of a combination of linear and nonlinear controller synthesis techniques and also allows adaptation of the life-extending controller module to augment a conventional performance controller of the rocket engine. The nonlinear aspect of the design is achieved using non-linear parameter optimization of a prescribed control structure.

Fatigue damage in fuel and oxidizer turbine blades is primarily caused by stress cycling during start-up, shutdown, and transient operations of a rocket engine. Fatigue damage in the turbine blades is one of the most serious causes for engine failure.

Description of the Reusable Rocket Engine

A functional diagram for the operation and control of the reusable rocket engine under consideration is presented in Figure 1. Liquid hydrogen and liquid oxygen are individually pressurized by separate closed cycle turbopumps. Pressurized cryogenic fuel and oxygen are pumped into two high-pressure preburners which feed the respective turbines with fuel-rich hot gas. The fuel and oxidizer turbopump speeds and hence the propellant flow into the main thrust chamber are controlled by the respective preburner pressures. The exhaust from each turbine is injected into the main combustion chamber where it burns with the remaining oxidizer and is expanded through the rocket nozzle to generate thrust. The oxygen flow into each of the two preburners are independently controlled by the respective servo-controlled valves. The plant outputs of interest are the O_2/H_2 mixture ratio the and main thrust chamber pressure.

A thermo-fluid-dynamic model of the rocket engine has been formulated for plant performance analysis and control systems synthesis. Standard lumped parameter methods have been used to approximate the partial differential equations describing mass, momentum, and energy conservation by a set of first-order differential equations. The plant model is constructed by causal interconnection of the primary subsystem models such as main thrust chamber, preburners, turbopumps, fuel and oxidizer supply header, and fixed nozzle regeneration cooling. The plant model has 18 state variables, two control inputs, and two controlled outputs.

Life-Extending Control System

The fundamental concept of life-extending control was developed initially for rocket engines, however, it has broad applications to other systems where both dynamic performance and structural durability are critical issues.

The architecture of the two-tier life-extending control (LEC) system is shown in Figure 2. The performance controller in the inner loop is designed to achieve a high level of dynamic performance. With a linearized plant (i.e., rocket engine) model, this controller can be designed using control synthesis techniques such as H_∞-based μ-synthesis to assure stability and performance robustness. The combination of plant dynamics and the performance controller in the inner loop becomes the augmented plant for the nonlinear damage controller design in the outer loop. The essential elements of the damage controller in the outer loop are: (i) a structural model that uses appropriate plant outputs to estimate the load conditions (e.g., stress at the critical locations); (ii) a time domain damage model that uses the load conditions to determine the damage rate and accumulation at the critical point(s); and (iii) the damage controller which is designed to reduce the damage rate and accumulation at the critical points, specifically under transient operations where the time-dependent load on the stressed structure is controllable.

Design of the Linear Performance Controller

This section presents the design of a sampled-data performance controller (inner loop) for the reusable rocket engine using the H_∞ (or induced L_2 norm to L_2 norm) controller synthesis technique. This controller design method minimizes the worst case gain between the energy of the exogenous inputs and the energy of the regulated outputs of a generalized plant. The performance controller requires very good low frequency disturbance rejection to prevent the damage controller output, u^{dam}, from causing a long settling time in the plant outputs.

Figure 3 shows the setup used for the synthesis of the induced L_2 norm controller for the rocket engine model with two inputs (fuel preburner oxidizer valve position and oxidizer preburner oxidizer valve position) and two outputs (main thrust chamber hot-gas pressure and O_2/H_2 mixture ratio). The plant model is obtained by first linearizing the 18 state nonlinear model of the rocket engine at a combustion pressure of 2550 psi and an O_2/H_2 ratio of 6.02. After linearization, the 18-state linear model is reduced to a 13-state linear model for the controller design via Hankel model order reduction, (maintaining model fidelity). The frequency-dependent performance weight, W_{perf}, consists of two components: W_{press}, which penalizes the tracking error of combustion chamber pressure W_{O_2/H_2} and, which penalizes the tracking error of the O_2/H_2 ratio. The frequency-dependent control signal weight, W_{cont}, consists of two components: W_{H_2} which penalizes the fuel position preburner oxidizer valve motion and W_{O_2} which penalizes the oxidizer preburner oxidizer valve motion. The objectives of these control signal weights are: (i) prevention of large oscillations in the feedback control signal that may cause valve saturation; and (ii) reduction of valve wear and tear due to high-frequency movements.

The parameters of both performance weights and control signal weights are initially selected based on the control system performance requirements and the knowledge of the plant dynamics; subsequently, the parameters are fine-tuned (Reference 1) based on the time-domain responses of the simulation experiments.

Using the generalized plant from Figure 3, a sampled-data controller is designed which is optimal in the induced L_2-norm sense. The controller provides acceptable reference signal tracking for the plant with reasonable control effort. It is found that reducing the order of the sampled-data controller from 21 states to 15 states causes no significant change in the controller dynamics from an input/output point of view. The 15-state controller is used in what follows.

Damage Modeling

Damage modeling is a critically important aspect of Life-Extending Control. The damage model is continuous-time-based for use in the controller design procedure as well for the implementation of the controller itself. Since the model is embedded in the life extending control loop, it should be as mathematically and/or computationally simple as possible, while representing the damage rate with sufficient accuracy for control purposes. Fatigue damage of the oxygen and hydrogen turbo-pump turbine blades is selected as the damage mechanism (and critical locations). The fatigue damage model, used in the controller design, assumes that damage only occurs during tensile loading. For the current application it will be seen that the damage mitigation is derived by reducing the mean stress on the turbine blades. Therefore, the damage rate equation (Reference 1) gives the damage increment for one stress cycle as:

$$\delta_{cyc} = 2\left(\frac{\sigma_a}{\sigma'_f - \sigma_m}\right)^{-1/b} \tag{1}$$

where σ_a is the stress amplitude, σ_m is the mean stress, $\sigma'_f = 223.589$ ksi is the fatigue strength coefficient, and b = -0.0858 is the fatigue strength exponent. The damage rate is calculated from the relation

$$\dot{D} = \left(\frac{\sigma_a}{\sigma'_f - \sigma_m}\right)^{-1/b} \frac{\Omega}{\pi} \tag{2}$$

where Ω is the frequency of vibration of the blades in units of rad/sec. This model is used for both on-line damage estimation and in the off-line optimization.

Design of the Nonlinear Damage Controller

The outer damage control loop is a cascaded combination of a structural estimator, a nonlinear fatigue damage model for the turbine blades, and a linear dynamic filter acting as the damage controller. The parameters of the dynamic filter are optimized to reduce the damage rate and accumulation at the critical points (i.e., fuel and oxidizer turbine blades) specifically under transient operations where the time-dependent load on the stressed structure is controllable. The nonlinear damage model is a simplified representation of the material behavior so that it can be incorporated in the outer control loop for real-time execution.

The damage controller is designed as a discrete-time linear structure by directly optimizing the elements of its A, B, C, and D matrices. To decrease the number of parameters to be optimized, the A matrix is constrained to be a diagonal matrix with distinct real elements.

The parameters of the linear dynamic filter are identified by minimizing a cost functional using nonlinear optimization. The cost functional is evaluated by the simulation, and the simulation results are a function of the current damage controller chosen by the optimization routine. Since damage controllers designed using this method are directly based on the maneuver used in the optimization process, the maneuver should be chosen to be broadly representative of all plant operation. The resulting damage controller is then validated by examining the results of various other typical maneuvers that the plant is expected to perform with this damage controller in the damage feedback loop.

The simulation on which the design of the damage controller is based is a ramp-up of the main thrust chamber hot gas pressure from a level of 2700 psi to 3000 psi at a rate of 3000 psi/sec, followed by a steady state at the final 3000 psi pressure for 500 ms (see Figure 4). The O_2/H_2 mixture ratio for this simulation is to be kept at a constant value of 6.02. After each simulation is performed, data representing the results of the simulation is sent to the cost functional subroutine. The value of accumulated damage for the O_2 and H_2 turbines at time t=0.6 seconds is also used for the calculation of the value of the cost functional.

The cost functional includes the effects of both reference signal tracking (dynamic) performance and damage in the turbine blades:

$$J^{tot} = J^{perf} + J^{dam}. \tag{3}$$

In the accumulated damage components, the initial accumulated damage is subtracted from the final damage at time NT=0.6 seconds to penalize the damage accumulated during the maneuver. The initial fatigue damage for both the O_2 and the H_2 turbine blades is assumed to be D(0)=0.1.

Since the governing equations and the cost functional are nonlinear in nature, a nonlinear programming technique is used to identify the optimal parameters of the damage controller. Also, in order to evaluate the cost functional, a time consuming simulation must be performed. Therefore, a nonlinear programming technique known as Sequential Quadratic Programming (SQP) is employed, which has the reputation of being able to efficiently and successfully solve a wide range of nonlinear programming problems in which the evaluation of the cost functional is a computationally intensive procedure. A Sequential Quadratic Programming (SQP) Fortran Software package developed by Gill *et al.* at Stanford University called NPSOL is utilized to design the damage controller.

Interaction effects between the damage controller and the performance controller are minimized by; (i) requiring a high level of dynamic performance through the cost functional for the nonlinear optimization of the damage controller, and (ii) by the inherent frequency separation of the high frequency damage loop and the lower frequency performance loop.

Simulation Results and Discussion

The damage controller is designed based on a transient which takes the chamber pressure from 2700 psi to 3000 psi (see Figures 5 to 10). Each plot displays two cases: (i) no damage control (i.e., $u(k) = u^{ff}(k) + u^{fb}(k)$); and (ii) with damage control (i.e., $u(k) = u^{ff}(k) + u^{fb}(k) + u^{dam}(k)$).

The chamber pressure trajectories for the two cases are compared in Figure 5. The damage controller causes a slower rise time, a longer settling time, and less overshoot in the chamber pressure transient. The damage controller also causes the O_2/H_2 ratio to deviate farther from the desired value of 6.02 than the case with no damage control as seen in Figure 6. However, the mixture ratio settles to 6.02 at steady state and remains within acceptable bounds throughout the duration of the simulation for both cases.

The damage rate and accumulation plots for the first 1 second of the 2700 psi - 3000 psi simulation are shown in Figures 7 to 10. Also, Table 1 summarizes the accumulated damage after this time interval for the two simulation cases (i.e., with and without damage control) for the two turbine blades.

The loss of dynamic response of chamber pressure (Figure 5) and the modestly increased excursion in mixture ratio is the cost incurred for the improved damage performance. It is also observed that the slope of the accumulated damage (damage rate) at t=1.0 seconds for the H_2 turbine blade (Figure 7) indicates that there may be a relatively large steady state damage rate for that turbine. If this is found to be the case for longer times then the steady state damage accumulation would far outweigh the transient damage.

The quality of the control designed above is now tested on a transient maneuver which takes the chamber pressure from 2100 psi to 3000 psi at a rate of 3000 psi/sec (see Figures 11 to 16). This maneuver involves a larger pressure increase than the nominal maneuver used to design the damage controller, and, therefore, is expected to produce a larger amount of damage accumulation.

A comparison of the chamber pressure trajectories with and without the damage controller is shown in Figure 11. As in the 2700 psi to 3000 psi case, the damage controller acts to "slow down" the transient as it approaches the final pressure of 3000 psi. Although the damage controller causes the O_2/H_2 ratio to deviate from the desired value of 6.02 more than it did during the 2700 psi to 3000 psi simulation, as seen in Figure 12, it settles to 6.02 at steady state and remains within acceptable bounds throughout the simulation. The mixture ratio is important in this application as an indicator of chamber temperature (and propellant utilization) since the damage model does not contain temperature effects.

The damage rate and accumulation plots for the first 1.2 seconds of the 2100 psi to 3000 psi simulation are shown in Figures 13 to 16. Table 2 summarizes the accumulated damage for this transient. In summary, the use of nonlinear optimization in the design of the damage controller achieved high levels of dynamic response and damage mitigation. The design approach is straightforward and the damage model worked well in this application. A detailed summary is presented in reference 1.

References

1) Lorenzo, C.F., Holmes, M.S., and Ray, A. "Design of Life Extending Controls Using Nonlinear Parameter Optimization", NASA TP 3700 to be published, 1998.

Table 1. Accumulated Damage (at t=1) for 2700 psi - 3000 psi Simulation.

	Without Damage Control	With Damage Control	Ratio
H_2 Blades	1.13×10^{-5}	6.15×10^{-6}	1.8
O_2 Blades	1.21×10^{-3}	3.45×10^{-5}	35.1

Table 2. Accumulated Damage (at t= 1.2) for 2100 psi - 3000 psi Simulation.

	Without Damage Control	With Damage Control	Ratio
H_2 Blades	2.46×10^{-5}	9.61×10^{-6}	2.6
O_2 Blades	2.48×10^{-3}	7.01×10^{-5}	35.4

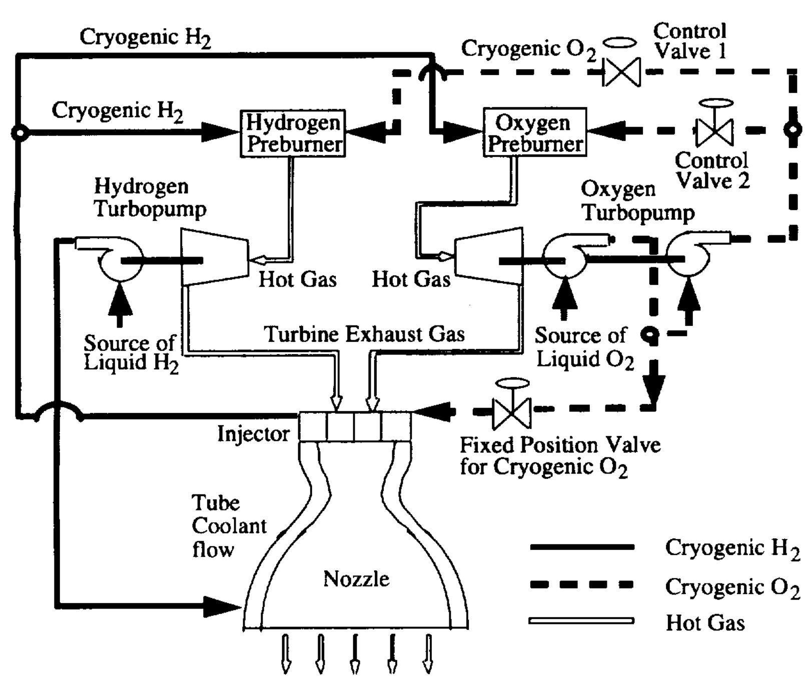

Fig. 1 Schematic diagram of reusable bi-propellant engine.

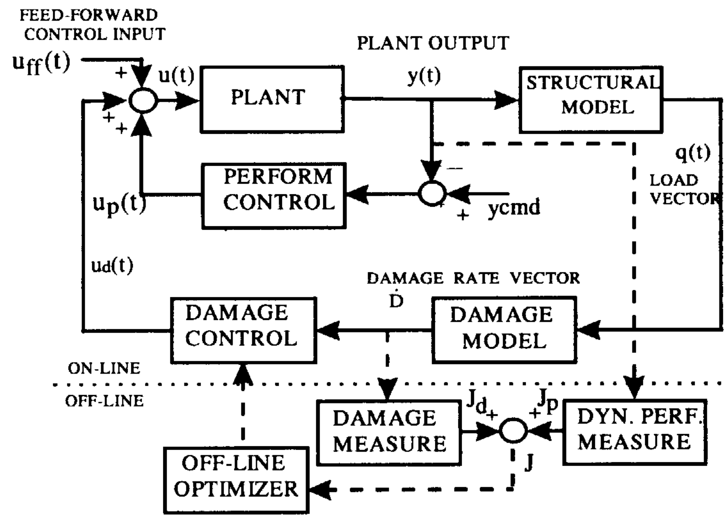

Fig. 2 Schematic diagram of Life-Extending Control System & off-line optimizer.

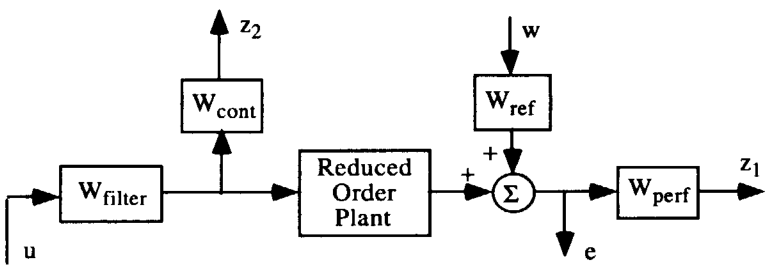

Fig. 3 Generalized plant for the linear controller synthesis of a reusable rocket engine.

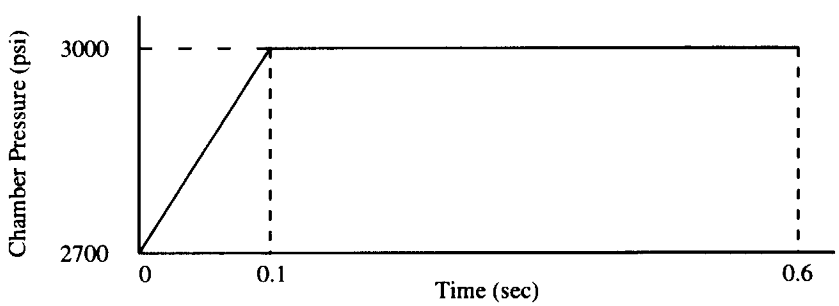

Fig. 4 Reference trajectory for chamber pressure.

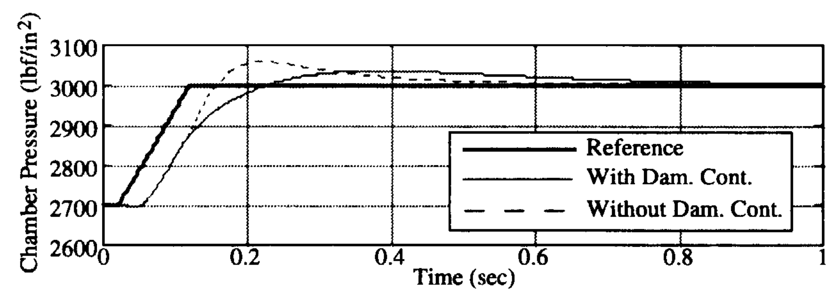

Fig. 5 Main combustion chamber hot gas pressure (2700 psi - 3000 psi).

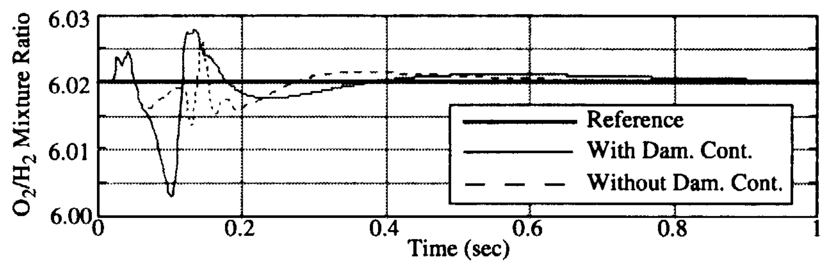

Fig. 6 O_2/H_2 mixture ratio (2700 psi - 3000 psi).

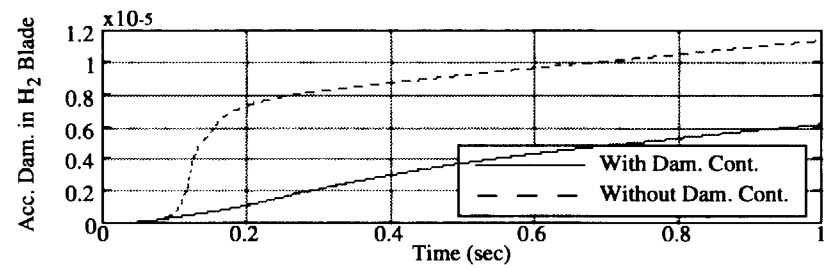

Fig. 7 Accumulated damage in H_2 blade (2700 psi - 3000 psi).

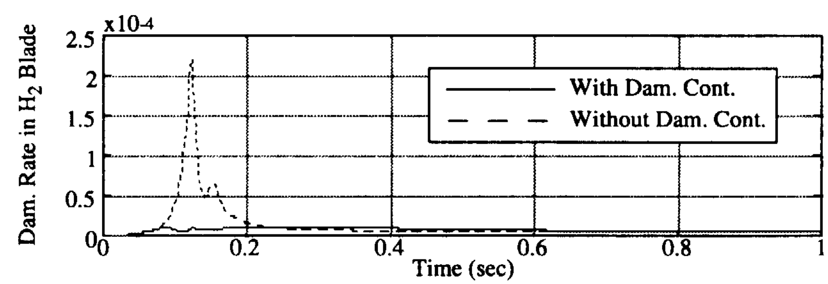

Fig. 8 Damage rate in H_2 blade (2700 psi - 3000 psi).

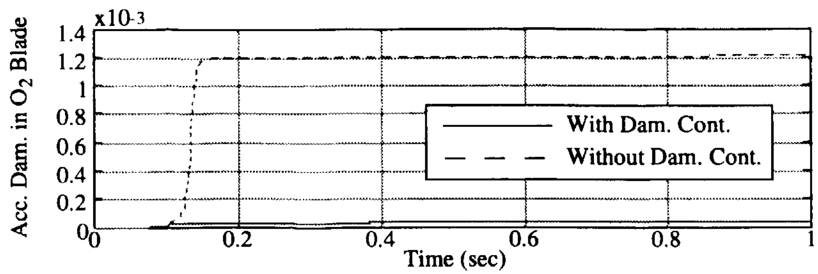

Fig. 9 Accumulated damage in O_2 blade (2700 psi - 3000 psi).

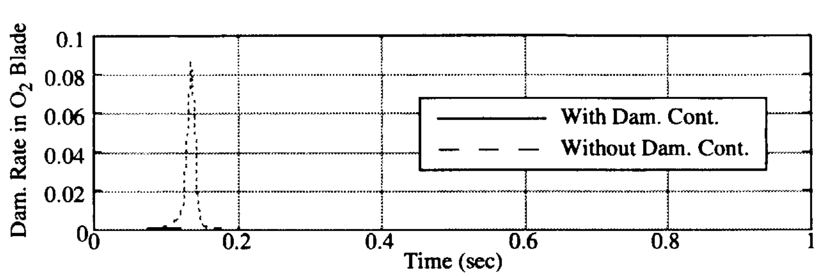

Fig. 10 Damage rate in O_2 blade (2700 psi - 3000 psi).

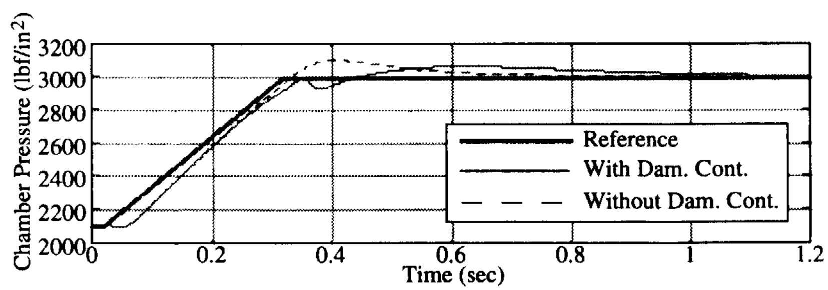

Fig. 11 Main combustion chamber hot gas pressure (2100 psi - 3000 psi).

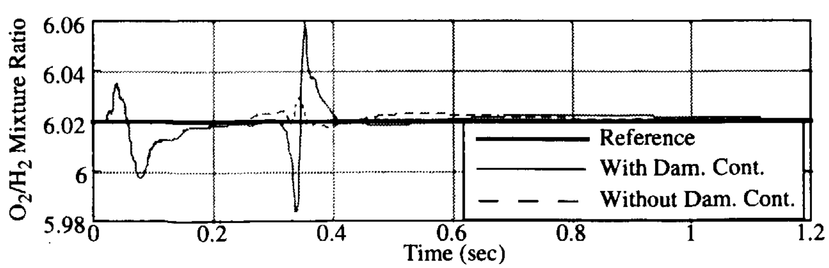

Fig. 12 O_2/H_2 mixture ratio (2100 psi - 3000 psi).

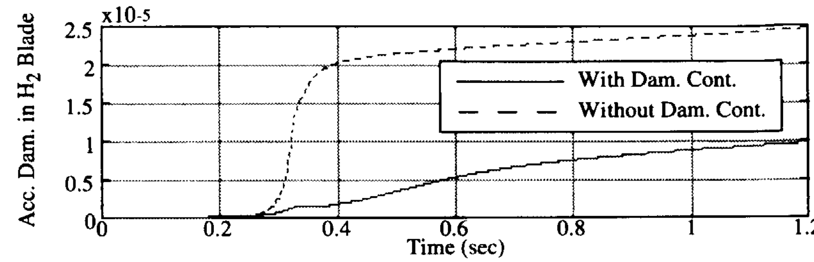

Fig. 13 Accumulated damage in the H_2 turbine blade (2100 psi - 3000 psi).

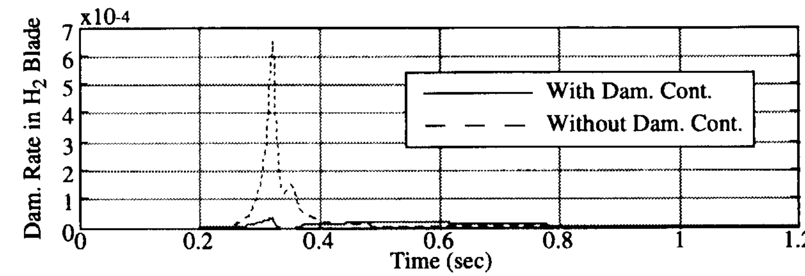

Fig. 14 Damage rate in the H_2 turbine blade (2100 psi - 3000 psi).

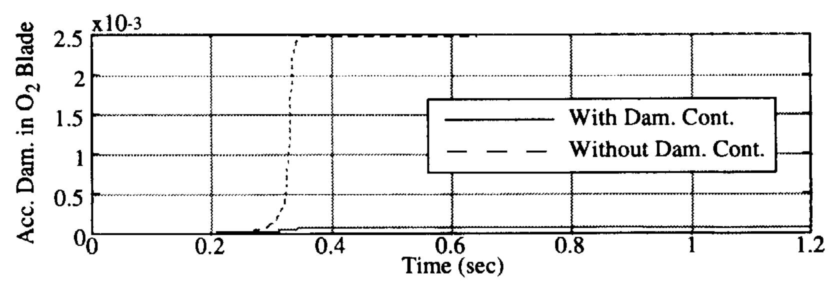

Fig. 15 Accumulated damage in the O_2 turbine blade (2100 psi - 3000 psi).

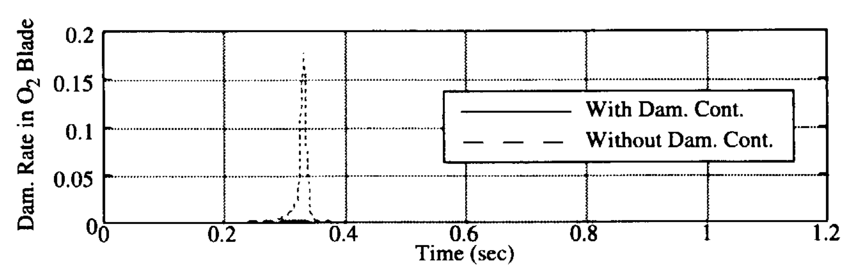

Fig. 16 Damage rate in the O_2 turbine blade (2100 psi - 3000 psi).

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13. ABSTRACT (*Maximum 200 words*)

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